Turbulence Measurements and Computations for the Prediction of Broadband Noise in High Bypass Ratio Fans.

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Work was performed under this grant with a view to providing the experimental and computational results needed to improve the prediction of broadband stator noise in large bypass ratio aircraft engines. The central hypothesis of our study was that a large fraction of this noise was generated by the fan tip leakage vortices. More specifically, that these vortices are a significant component of the fan wake turbulence and they contain turbulent eddies of a type that can produce significant broadband noise. To test this hypothesis we originally proposed experimental work and computations with the following objectives:

(1) to build a large scale two-dimensional cascade with a tip gap and a stationary endwall that, as far as possible, simulates the fan tip geometry,
(2) to build a moving endwall for use with the large scale cascade,
(3) to measure, in detail, the turbulence structure and spectrum generated by the blade wake and tip leakage vortex, for both endwall configurations,
(4) to use the CFD to compute the flow and turbulence distributions for both the experimental configurations and the ADP fan,
(5) to provide the experimental and CFD results for the cascades and the physical understanding gained from their study as a basis for improving the broadband noise prediction method.

In large part these objectives have been achieved. The most important acheivements and findings of our experimental and computational efforts are summarized below. The bibliography at the end of this report includes a list of all publications produced to date under this project. Note that this list is necessarily incomplete the task of publication (particularly in journal papers) continues.

Experiments

An 8 blade, 7 passage linear compressor cascade wind tunnel with stationary endwall was built, by adapting a turbine cascade facility (Devenport *et al.*, 1997). GE RotorB section blades were used, since at low speed these produce a blade loading distribution that is very similar to that of large bypass ratio aircraft engine fan blades. The blades were mounted in a system that allowed the tip gap to be varied. The flowfield downstream of the cascade was measured using four sensor hot-wire anemometers, from which the mean velocity field , the turbulence stress field and velocity spectra were obtained. Oil flow visualizations were done on the endwall underneath the blade row. Also studied were the effects of tip gap height, and blade boundary layer trip variations. The wind tunnel and these measurements are discussed in detail by Muthanna (1998) and Muthanna *et al.* (1998). In short, these measurements showed that (at least with a stationary endwall) the tip-leakage vortex dominates the turbulence structure of the flow, making it a likely source of broadband noise. Turbulence levels in the vortex are larger, and decay more slowly than in the blade wakes. The axial velocity deficit in the tip leakage vortex is large compated to the tangential flow around it, and this deficit is directly responsible for most of the turbulence production.

Two-point 3-component space-time correlations of fluctuating velocities were measured in the same flow, to examine the form of the eddies contained within the tip leakage vortex and to reveal the form of the upwash wavenumber frequency spectrum that is used to define the turbulence for the purposes of broadband noise calculations.

These results, the first of their type for a compressor/fan cascade, are described in detail by Wenger (1998) and Wenger *et al.* (1998). These measurements showed the tip leakage vortex contains large scale eddies, elongated along an axis roughly 20° from that of the tip vortex itself. It seems probable, based upon comparison with free vortex simulations that these eddies form part of larger helical structures associated with instability in the vortex produced by its axial velocity deficit. Most importantly the eddies result in an extremely anisotropic space-time correlation function. This complicates the noise prediction problem, since it is likely to make the noise produced by the stator wake interaction a strong function of engine operating point, and suggests that fairly sophisticated turbulence models will be needed.

A large-scale moving end-wall system was designed and built for the cascade tunnel where it was used to simulate the effects of the relative motion between the blade tips and casing upon the flow. Detailed 3-component hot wire mean flow and turbulence measurements were made at various locations downstream the cascade as a function of tip gap and were compared with the stationary endwall measurements described above. The unique moving endwall apparatus and these measurements are described in detail by Wang *et al.* (1999) and Wang (2000). Relative motion between the blade tips and endwall was found to have a substantial effect on the overall form of the tip leakage vortex, flattening it, and moving it further across the endwall. However, it was found that the relative motion did not fundamentally alter the mean-flow characteristics of the vortex (it still being dominated by its axial velocity deficit) or the mechanism through which it generates turbulence (the axial mean velocity gradients). We therefore concluded that the anisotropic eddy structure observed in the two point measurements is likely to be persist in the presence of wall motion and thus be a feature of real engine flows.

Data from these measurements have been distributed to the aeroacoustic community through our web site www.aoe.vt.edu/flowdata/ast/ast.html, and prediction efforts that employ the data are currently underway at Virginia Tech, Florida Atlantic University, and Pratt and Whitney.

Computations

Computations were begun under the administration of Professor John Moore of the Mechanical Engineering Department and Virginia Tech, the original co-PI of this project. In collaboration with Joan Moore, he performed a number of preliminary CFD calculations of the cascade wind tunnel flow, and related configurations. These computations were reported in a series of informal reports published on their web site www.aoe.vt.edu/flowdata/ast/quiet/index.html. During the second year of the project, however, Professor Moore retired from the university and project, and this component of the study was taken over by Professor Saad Ragab of the Engineering Science and Mechanics Department.

In the second year, the main contribution of the computational effort is the development of an unstructured RANS solver for 2D cascades (Shin et al. (1999) and Shin and Ragab (2000)). The use of unstructured grids was necessary because the GE rotor B, which is the model used in experimental work, has a high stagger angle (56.9 degrees) for which structured grids would be in adequate. The new code solves the incompressible RANS equations. An implicit scheme is used for time integration which is based on linearized Euler backward method. Artificial compressibility method is used to couple the velocity and pressure fields and inviscid fluxes are calculated based on Roe's flux difference splitting. Second order accuracy is attained by formulating gradient based on Green's theorem. For turbulence model Spalart-Allmaras model is used. Viscous grid near solid wall is generated by advancing layer method and Delaunay triangulation is used for the rest of the domain.

To validate our code, comparisons are made with available computational and experimental results for NACA0012 airfoil, double-circular arc and GE rotor B section cascades. For double-circular arc cascade, blade surface pressure distributions are compared with experiment. Spalart-Allmaras model predicts a leading edge laminar separation bubble and a trailing edge separation of tubulent boundary layer. These results are in agreement with experimental observation. Total velocity profiles in the wake of GE rotor B section are compared with measurement and good agreement is achieved by Spalart-Allmaras model.

The computational effort is continuing to develop a 3D RANS solver for the tip clearance flow. Presently, the code solves the 3D Euler equations and extension to turbulent flow is underway.

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